Cube Flux Method to Generate Spacecraft Thermal Environments

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Need for Spacecraft Thermal Environment

- Spacecrafts are exposed to various environments that are not present at the surface of the earth, like plasmas, neutral gases, x-rays, ultraviolet (UV) irradiation, high energy charged particles, meteoroids, and orbital debris. The interaction of these environments with spacecraft cause degradation of materials, contamination, spacecraft glow, charging, thermal changes, excitation, radiation damage, and induced background interference.

- The damaging effects of natural space and atmospheric environments pose difficult challenges for spacecraft designers.

- ISS and Orbiter thermal models were used to develop a method to determine the environments around the ISS/Orbiter in Earth and Mars orbits.

- This method can be applied for any space vehicle orbiting any planet or for inter-planet travel with applicable space travel fluxes.

Flux Cube Method

- The cube flux method has been previously developed by Lockheed Martin; similar principle of flux generation has been adopted in this study. The method presented here is efficient and simple since the orbiter model and flux generation routine (**HTFLXCAL**) are run from Thermal Desktop® in a single run, and Solar and IR fluxes for all cube locations are generated, and the sink temperatures for given optical properties are also produced.

- Complete procedure with HTFLXCAL routine and results have been outlined in the paper submitted.

- The sink temperatures generation routine for required materials using Solar and IR fluxes has been incorporated in the flux generation routine.

- ISS/Shuttle thermal environments were compared for Earth and Mars.

- The method was also applied on a Satellite in GEO and LEO for environments comparison.

Solar and IR Fluxes

- **Sun's rate of emission from the photosphere**:

  By applying Stefan-Boltzmann Law:

  $I = \sigma \cdot T^4$ (assuming emissivity = 1.) Energy Flux Watts/m^2

  σ = Stefan-Boltzmann's constant = 5.67×10^{-8} W/m^2/K^4

  T = Sun photosphere temperature (Kelvin) = 6000 K (max)

  $I = 73.49 \times 10^6$ W/m^2 (Energy flux from Sun)

- **Total energy emitted by Sun's photosphere:**

  $E_p = I \times PA$ Where PA = Sun's photosphere surface area = $4 \cdot \pi \cdot r^2$,
  where $r = 647 \times 10^6$ m (photosphere radius)

  $E_p = 3.866 \times 10^{26}$ Watts

Solar and IR Fluxes

- **Earth Solar Flux (Qsol):**

At the distance of Earth, the sphere will have a radius equal to Earth's average distance from the Sun (150×10^9 m). So Sun energy (W) will be spread over photosphere of radius $r_p = 150 \times 10^9$ m.

Energy received by Earth:

$Q_{sol} = E_p / 4.\pi.\, r_p^2$

$Q_{sol} = E_p / 4.\pi.\, (150 \times 10^9)^2 = 1367.23$ W/m^2 = 433.41 BTU/hr.ft^2 ~ 434 Btu/hr.ft^2 (Earth Solar Constant)

- **Earth IR Flux (Qir):**

Total energy falling on an average Earth area:

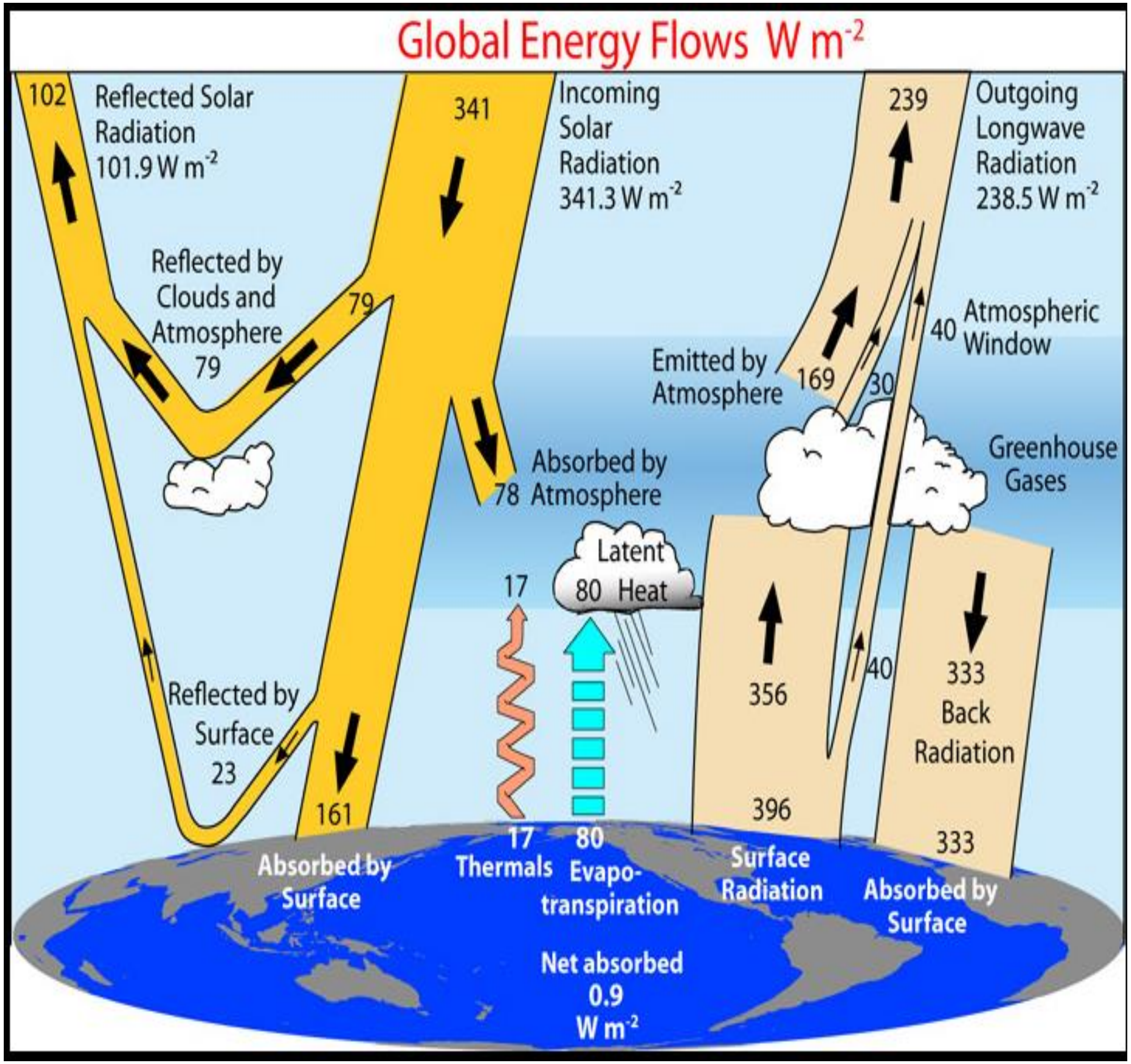
E = Total Energy Intercepted / Surface Area of Earth = Solar Constant x Area of Earth Disk / Surface Area of Earth

$E = Q_{sol} \times (\pi \, . \, r_e^2) / (4 \, . \, \pi \, . \, r_e^2) = Q_{sol} / 4 = 341.81$ W/m^2

Earth Planetary Albedo is estimated to be 30%, or 0.3. Therefore, the absorbed energy is 70%, or 0.7 times of incoming energy.

Earth IR = Q_{ir} = E x 0.7 = 239.26 W/m^2 = 75.85 Btu/hr.ft^2 ~ 76 Btu/hr.ft^2

Earth Global Energy Distribution



Generating Cube Qsol and Qir

- Total heat absorbed by a cube:

$Q_{absorbed} = \alpha_{sol} \, . \, Q_{sol} + \varepsilon_{ir} \, . \, Q_{ir}$

α_{sol} = Solar absorptivity of the material for which sink temperature is required

ε_{ir} = Infrared emissivity of the material for which sink temperature is required

Q_{sol} = Absorbed flux - comprised of following four parts:

1. **Direct Solar** - incident onto the surface in question.
2. **Reflected Solar** - direct solar reflected off of other ISS hardware surfaces to the surface in question.
3. **Direct Albedo** - solar reflected off of planet diffused to space called Albedo to the surface in question.
4. **Reflected Albedo** - Solar reflected off of planet and re-reflected off of ISS hardware surfaces onto the surface in question.

- The above solar fluxes Q_{sol} (#1 to #4) are obtained by running ISS model in TD®
- Surface temperatures are calculated by SINDA in TD® and generated as an output array for all 6 surfaces of each cube.
- The above two files with Qsolar and Temperatures for each surface are input to SINDA model (HTFLXCAL) to calculate the Infrared flux (Q_{ir}) for each cube.
- HTFLXCAL calculates the total infrared thermal radiation incident on each surface of a cube through heat balance with the SINDA calculated cube surface temperatures and the TD® supplied incident solar flux. The cube surfaces are adiabatic.

$$Q_{absorbed} = \alpha_{sol} \, . \, Q_{sol} + \varepsilon_{ir} \, . \, Q_{ir} = \sigma \, . \, \varepsilon_{ir} \, . \, (T_{surface}^4 - T_{space}^4)$$

$$Q_{ir} = \sigma . \, T_{surface}^4 - (\alpha_{sol} / \varepsilon_{ir}) \, . \, Q_{sol} \qquad \text{for } T_{space} \approx 0\ °R$$

$$Q_{ir} = \sigma . \, T_{surface}^4 - Q_{sol}$$

Cube surfaces are treated as blackbody so $\alpha_{sol} / \varepsilon_{ir = 1}$

Space Environment Sink Temperature

$Q_{radiated} = Q_{absorbed}$ (1)

$Q_{radiated} = \sigma \cdot \varepsilon_{ir} \cdot (T_{surface}^4 - T_{space}^4)$

$T_{surface}$ – cube surface temperature

T_{space} – deep space temperature = -459.67 °F ≈ 0 °R

$Q_{radiated} = \sigma \cdot \varepsilon_{ir} \cdot T_{surface}^4$ (2)

Substituting (2) in (1) above

$\sigma \cdot \varepsilon_{ir} \cdot T_{surface}^4 = Q_{absorbed}$ (3)

$T_{surface} = (Q_{absorbed} / \sigma \cdot \varepsilon_{ir})^{1/4}$ (4)

$Q_{absorbed} = \alpha_s \cdot Q_{sol} + \varepsilon_{ir} \cdot Q_{ir}$ (5)

$$T_{surface} := \left[\frac{\left(\frac{\alpha_s}{\varepsilon_{ir}}\right) \cdot Q_{sol} + Q_{ir}}{\sigma} \right]^{\frac{1}{4}}$$ **(6)**

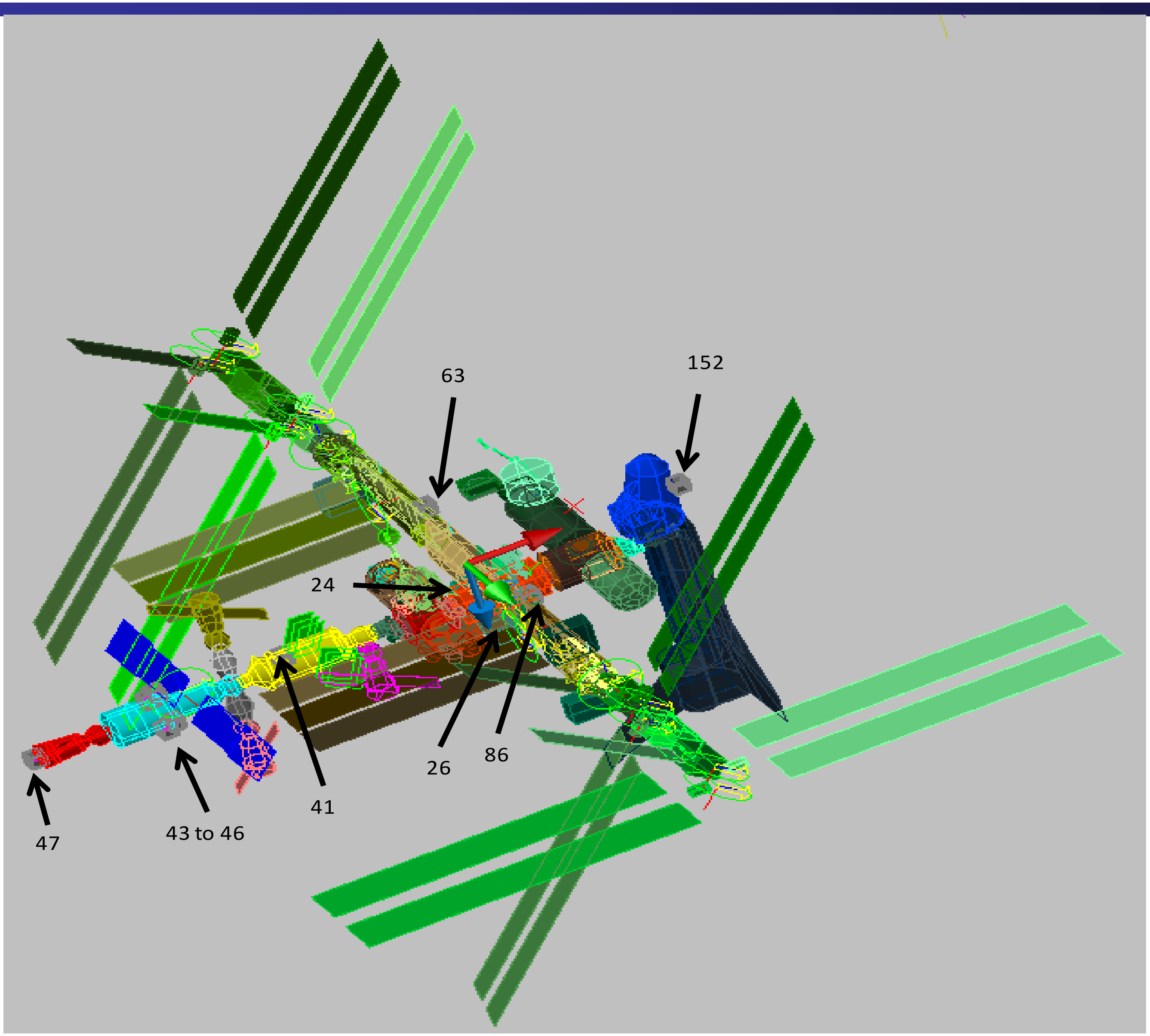
$\mathbf{T_{sink} = T_{surface}}$

Sink temperature is the temperature a surface comes to if only influenced by external radiant heat exchange

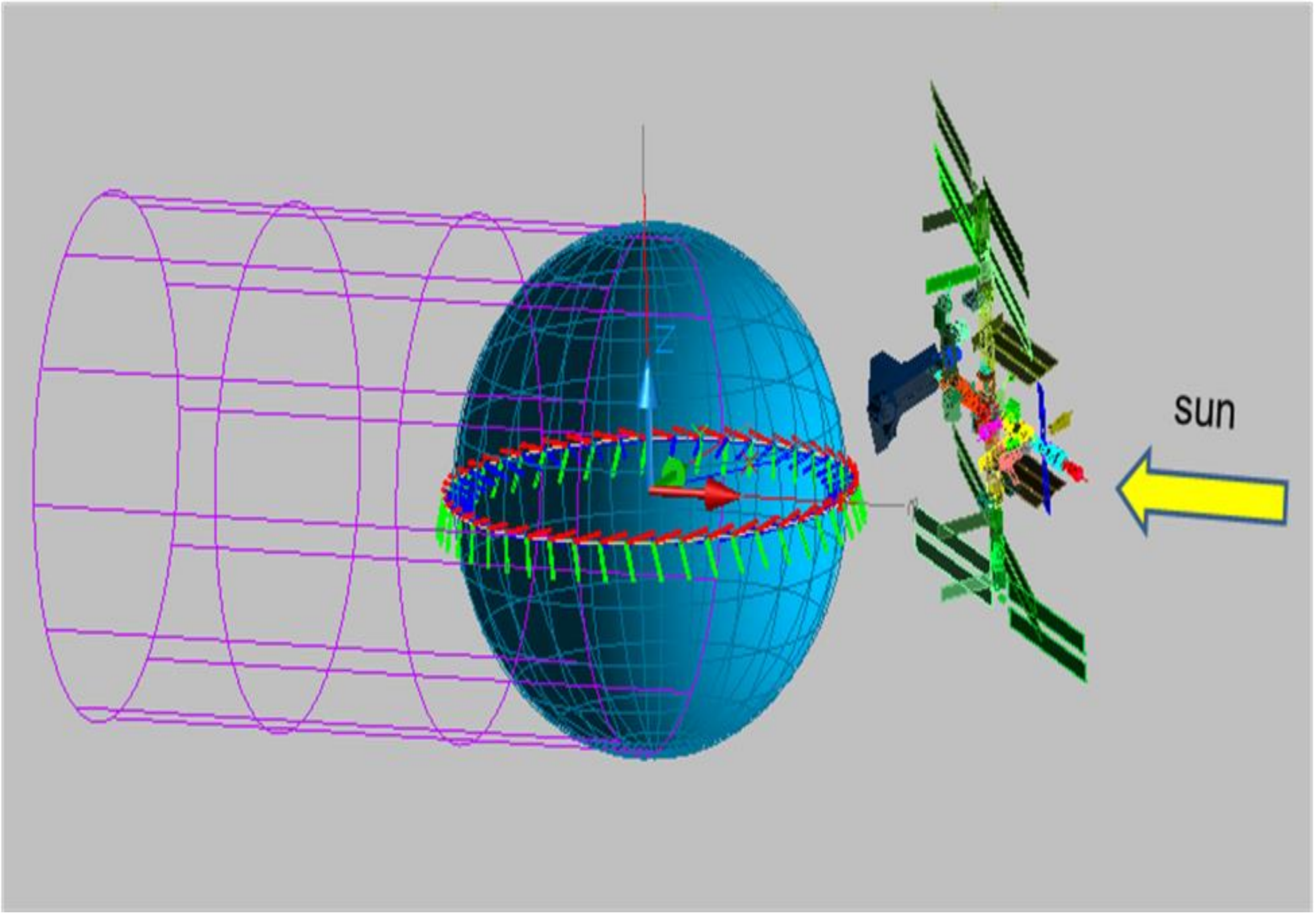
Assumptions and Specifications

1. Flux cubes dimensions are 1x1x1 ft^3.
2. Flux cubes are arithmetic nodes, i.e. have zero capacitance.
3. Flux cubes inner surfaces are adiabatic, i.e. inner surfaces are not radiating to each other and cube surfaces are not connected to each other. Inner surfaces are not active.
4. Cube outer surfaces are optically active and have absorptivity (α) and emissivity (ε) as one (1.0).
5. Cubes are one foot above the ISS/Orbiter surfaces.
6. ISS/Orbiter model has articulators which are turned active to generate radiation conductors.
7. One orbital cycle is divided into 48 increments (in 0 to 360 revolving angle).
8. ISS/Orbiter altitude is 200 nm, with beta = 0 degree.
9. Attitude is Yaw (Z axis), Pitch (Y axis), Roll (X axis) = -15,0,-15, with Z-Nadir (facing Earth).
10. Following constants were used for analysis performed in this study:
    - Solar Constant = 444.0 Btu/hr.ft^2
    - Albedo = 0.3
    - Earth IR = 77 Btu/hr.ft^2
11. Cube are named such that cubes submodels appear at the beginning of the 'Submodel Node Tree' in TD®, so that solar flux arrays in '**Heatrates.hra**' file appear starting from array number 2. Array 1 is Time Array.
12. In **NodeDescription.txt** file node description **s**hould be in the same order as submodels appearing in 'Submodel Node Tree'.

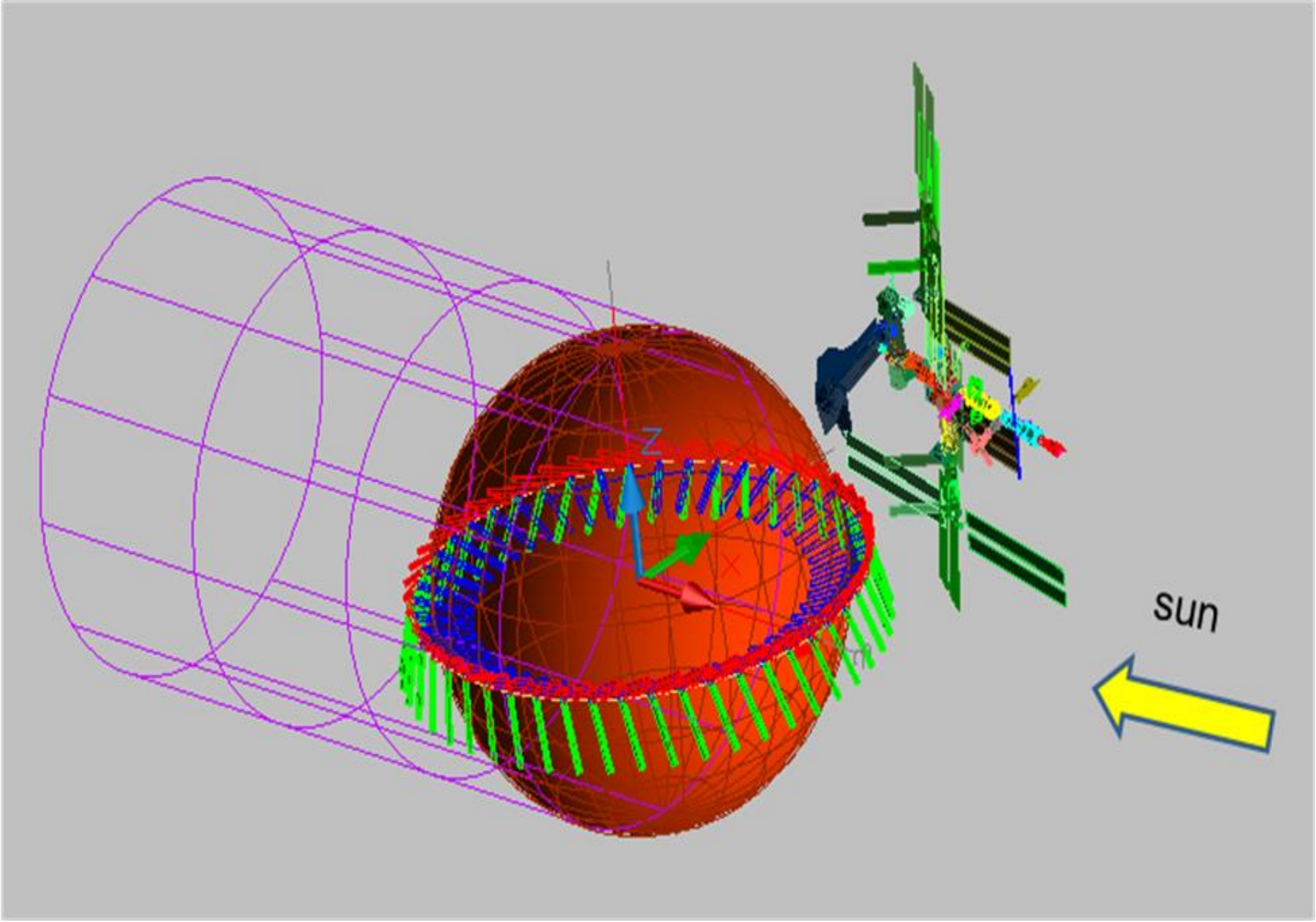
ISS/Orbiter Model with Cubes



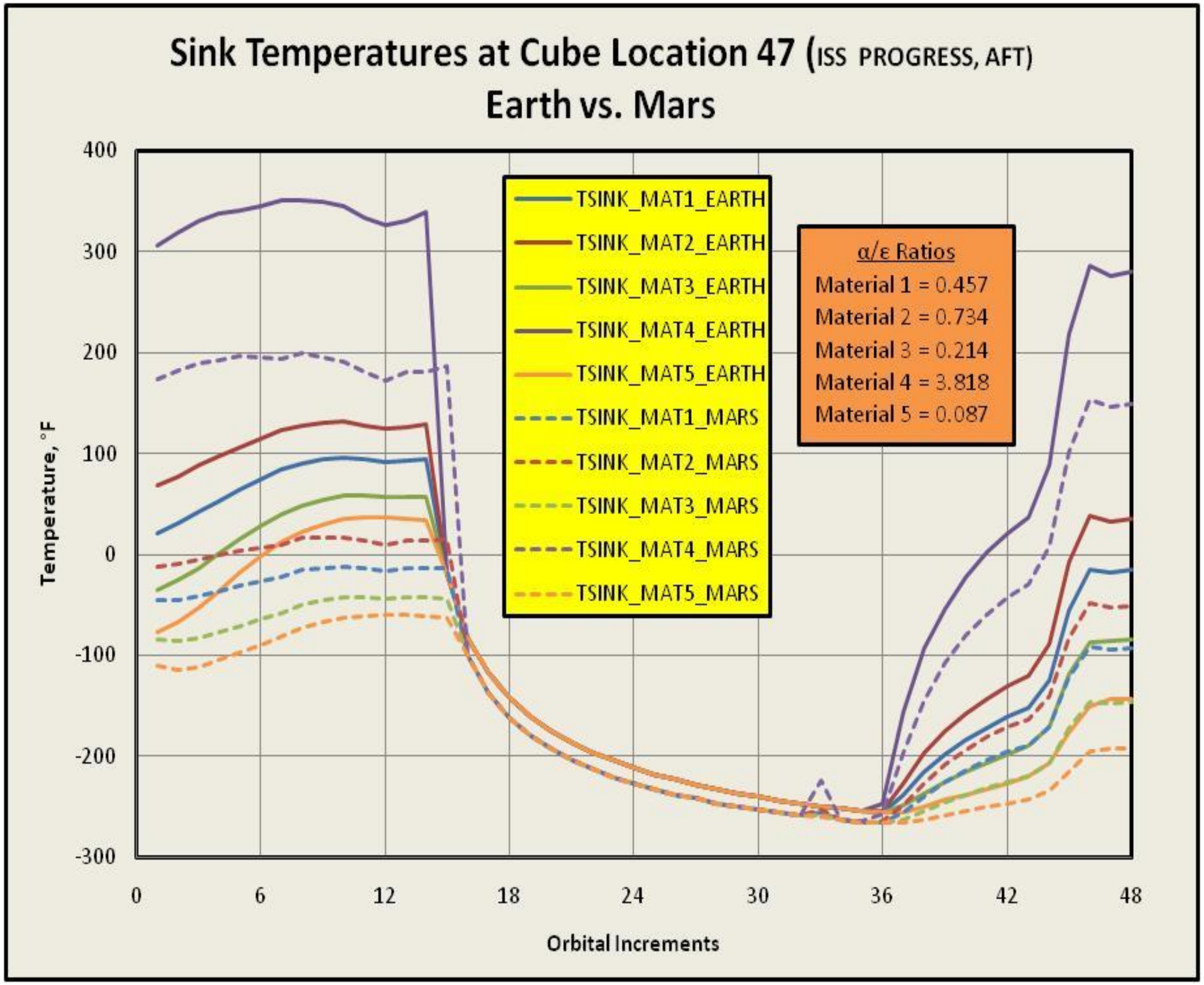
ISS/Shuttle in Earth Orbit



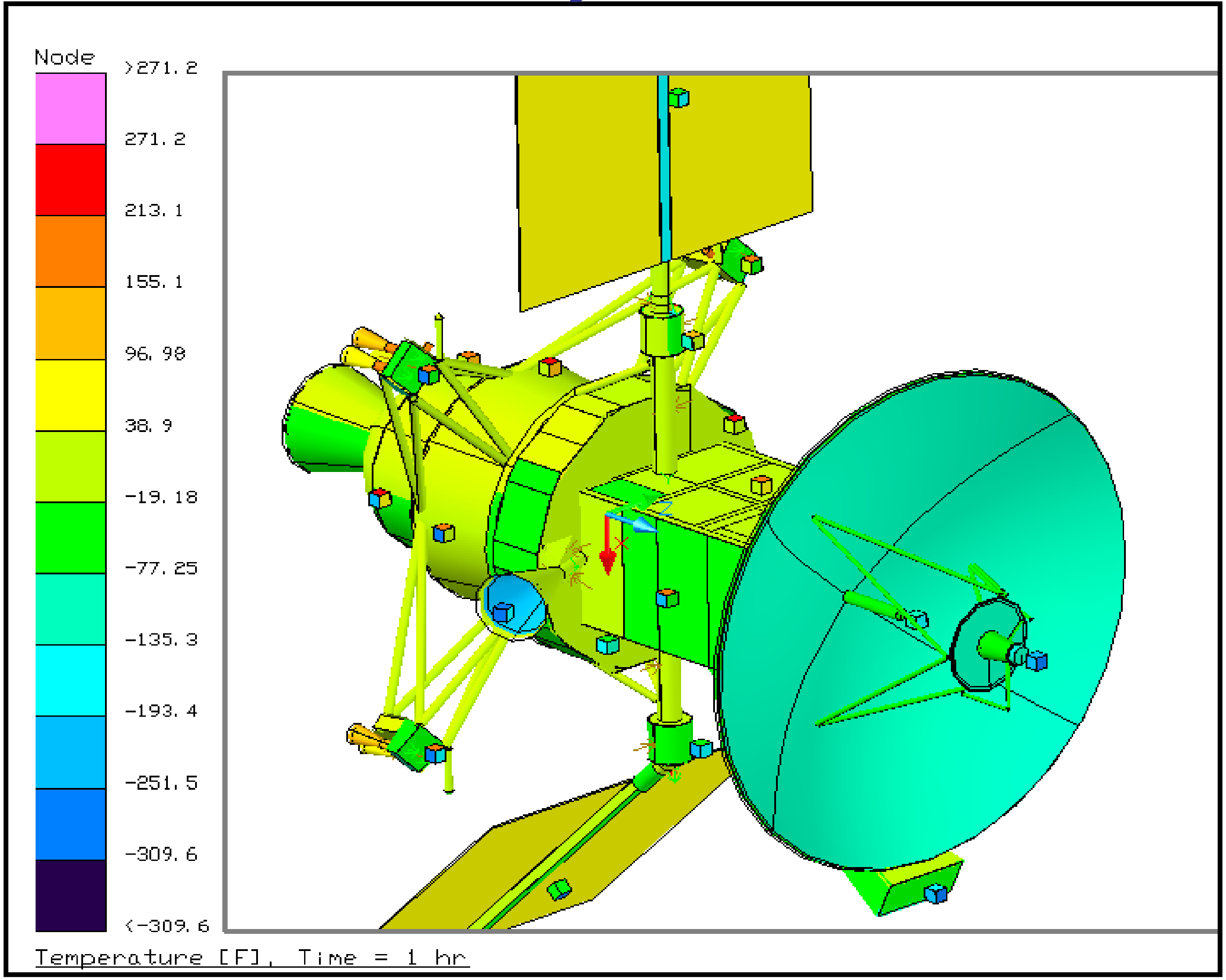
ISS/Shuttle in Mars Orbit



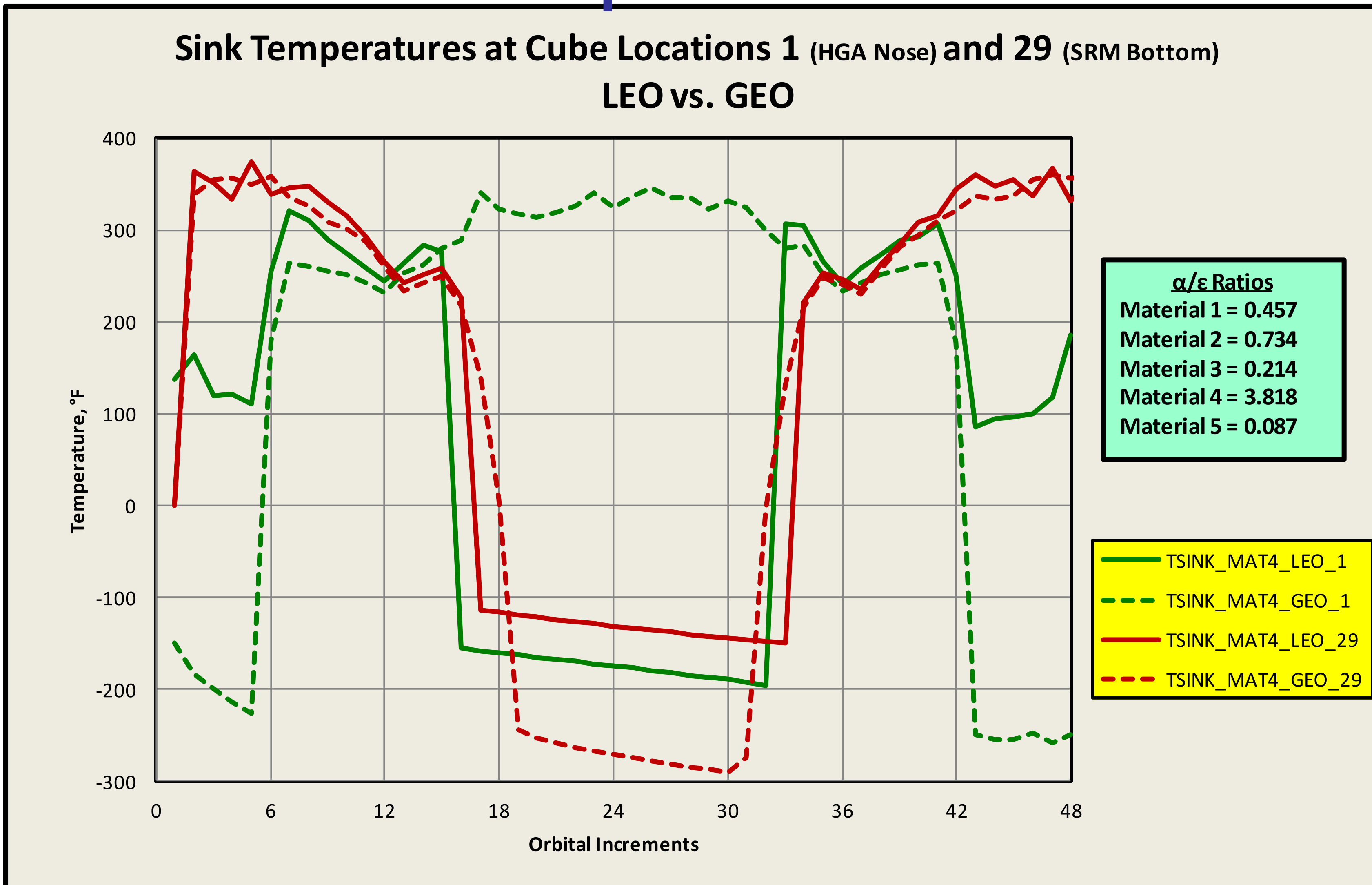
Sink Temperature Comparison of ISS/Shuttle Progress, Aft Location in Earth vs. Mars Orbits



Thermal Contours of Satellite and Cubes in Geosynchronous Orbit



LEO and GEO Sink Temperatures Comparison



Conclusions and Comments

1. The procedure can be applied to any planet to generate environments around the satellite.
2. Results from the model developed were verified by hand calculations.
3. To determine environments around a satellite its thermal model with cubes at critical locations will be required to determine solar and IR fluxes and sink temperatures at those locations.
4. A database of cube fluxes at required attitudes and betas can be developed for an orbiting satellite.
5. Once a fluxes database is generated for a range of orbital beta angle and orbiter attitudes the max and min sink temperatures for six modes, namely instantaneous min, instantaneous max, average min, average max, Dayside average, and Night time average can be determined.
6. The sink temperatures for EVA purposes can be generated or compared using the method outlined in here.
7. Mars environments in dayside were found 100 to 150 °F cooler than Earth orbit, and in nightside (no direct solar or Albedo fluxes) were found 20 °F cooler than the Earth orbit for materials optical properties, orbit definition, and the ISS/Shuttle location selected.

Conclusions and Comments

8. The method can be applied to both orbiting and interplanetary traveling spacecraft as far as admissible travel path is defined. The interplanetary path would calculate applied Solar, Albedo and Planets IR the spacecraft is subjected to when traveling from one planet to another. Some modifications in TD® Case Set 0 will be needed for TIMEND and Output Increment.

9. For interplanetary analysis, the best option would probably be a combination of the following:
    1. Define the planet 1 regular orbit
    2. Define a vector list from the regular orbit to a point where Planet 1 has negligible effect on the spacecraft
    3. Define the elliptical heliocentric transfer orbit
    4. Define a vector list from the point where Planet 2 has negligible effect on the spacecraft to the Planet 2 orbit
    5. Define the planet 2 regular orbit

10. A good practice would be to create a sphere and use it with a vector list to determine how close the spacecraft must be to the planet to receive a significant amount of energy from the planet. If the spacecraft can receive significant energy at a large distance, it may make sense to solve using the vector lists and heliocentric orbits at the same time. The heliocentric orbit has the correct solar flux (it treats the Sun as a finite black body). When solving two orbits simultaneously, the common sources from one of the orbits should be excluded. In the case of a planetary and heliocentric obit, the solar calculation from the planetary orbit should be excluded. One would also need to be mindful of eclipses.

Generated Solar and IR Fluxes at a Cube Location (Earth Orbit)

```
EVA START TIME (HOUR) =     16.90000
C TIME ARRAY
1000 =
   16.93193,   16.96386,   16.99579,   17.02771,   17.05964,   17.09157
   17.12350,   17.15543,   17.18736,   17.21929,   17.25122,   17.28314
   17.31507,   17.34700,   17.37893,   17.41086,   17.44279,   17.47472
   17.50665,   17.53857,   17.57050,   17.60243,   17.63436,   17.66629
   17.69822,   17.73015,   17.76208,   17.79400,   17.82593,   17.85786
   17.88979,   17.92172,   17.95365,   17.98558,   18.01751,   18.04943
   18.08136,   18.11329,   18.14522,   18.17715,   18.20908,   18.24100
   18.27294,   18.30486,   18.33679,   18.36872,   18.40065,   18.43258

C  GROUP 152 - SHUTTLE NOSE, BACKSIDE
 2152=            $ INCIDENT SOLAR FLUX ARRAY  - LOCATION -  152
   58.84053,   33.03804,   31.10059,   28.39160,   24.62483,   21.15456
   18.12162,   14.53844,   10.91728,    7.60940,    3.29098,    0.59027
    0.02211,    0.38010,    0.00000,    0.00000,    0.00000,    0.00000
    0.00000,    0.00000,    0.00000,    0.00000,    0.00000,    0.00000
    0.00000,    0.00000,    0.00000,    0.00000,    0.00000,    0.00000
    0.00000,    0.00000,    0.00000,  128.79700,  123.24378,  124.33167
  132.76498,  143.50902,  150.62096,  161.36725,  167.76506,  167.22888
  166.86443,  167.75914,  150.30550,  144.65431,  128.21388,  126.04385

C  GROUP 152 - SHUTTLE NOSE, BACKSIDE
 3152=            $ INCIDENT IR FLUX ARRAY    - LOCATION -  152
   34.51741,   28.21892,   23.47870,   20.87336,   17.97002,   16.57041
   14.94577,   13.77933,   12.87545,   12.08064,   10.75601,    9.91682
    9.39068,    8.05332,    6.62710,    5.44979,    4.85847,    4.98695
    4.03009,    3.72052,    3.45872,    3.47024,    4.63325,    2.90809
    2.88645,    2.45449,    2.43088,    2.28691,    2.19665,    1.94899
    2.60995,    2.00918,    1.79609,    2.03739,   19.16252,   40.32675
   61.36478,   72.61404,   77.56471,   78.67237,   77.97537,   63.69867
   68.25182,   63.63826,   56.36827,   49.50508,   43.02991,   38.74050
```

Sink Temperatures.US5 File (Extract)

- **SINK TEMPERATURES FOR: GROUP 152 - SHUTTLE NOSE, BACKSIDE**

NUMBER OF MATERIALS = 5
Material 1, Absorptivity = 0.380, Emissivity = 0.830, Ratio (a/e) = 0.4578
Material 2, Absorptivity = 0.580, Emissivity = 0.790, Ratio (a/e) = 0.7342
Material 3, Absorptivity = 0.180, Emissivity = 0.840, Ratio (a/e) = 0.2143
Material 4, Absorptivity = 0.420, Emissivity = 0.110, Ratio (a/e) = 3.8182
Material 5, Absorptivity = 0.070, Emissivity = 0.800, Ratio (a/e) = 0.0875

SINK TEMPERATURES FOR 5 MATERIALS
TIME = HOURS, QSOL AND QIR = BTU/HR/FT**2, TEMP = DEGF

TIME	QSOL	QIR	TSINK_MAT1	TSINK_MAT2	TSINK_MAT3	TSINK_MAT4	TSINK_MAT5
16.93193	58.84053	34.51741	-24.73	1.57	-52.69	163.75	-69.86
16.96386	33.03804	28.21892	-61.12	-41.59	-81.08	87.96	-92.86
16.99579	31.10059	23.47870	-74.74	-54.46	-95.74	76.86	-108.29
17.02771	28.39160	20.87336	-84.96	-64.91	-105.77	64.20	-118.24
17.05964	24.62483	17.97002	-98.49	-79.08	-118.65	45.72	-130.74

18.33679	150.30550	56.36827	59.99	98.61	16.92	318.92	-11.11
18.36872	144.65431	49.50508	49.89	89.15	5.66	309.98	-23.49
18.40065	128.21388	43.02991	33.71	72.01	-9.53	286.81	-38.10
18.43258	126.04385	38.74050	27.18	66.21	-17.32	282.36	-47.09